CALIFORNIA
ENERGY
COMMISSION

INCREASED EFFICIENCY OF AIR CONDITIONERS AND HEAT PUMPS USING ADVANCED POWER ELECTRONICS

CONSULTANT REPORT

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Gray Davis, *Governor*

Legal Notice

Acknowledgements

ESI would like to thank the following individuals for their contributions to this project.

Michael Martin, California Energy Commission Contract Project Manager for most of the project, who provided the overall program direction with his vast experience and knowledge in air conditioner testing and certification.

Philip Spartz took over the project as Commission Contract Manager towards the end and came up to speed in a very short time. He managed the final phase of this project, providing emphasis on transitioning to the market place.

Jim Sprout, who started as a consultant and ended up as Vice President of Engineering at ESI, contributed to both to electronics technology and cost share.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for "Increased Efficiency of Refrigerators and Air Conditioners Using Advanced Power Electronics," Contract Number: 500-98-021. The report is entitled "Increased efficiency of Air Conditioners and Heat Pumps Using Advanced Power Electronics." This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

This report describes work performed by Energy Savers International (ESI) between May 1999 and June 2001 on the project entitled "Increased Energy Efficiency of Refrigerators and Air Conditioners Using Advanced Power Electronics." The California Energy Commission’s Public Interest Energy Research (PIER) program provided $411,614 in funding for this project. ESI‘s original cost share of $114,000 increased to $242,131 by project end in June 2001

Background

Assuming that the growing energy needs of the United States were met only through building additional power plants, an estimated 1300 new plants of 300 MW each would be needed by the year 2020. However, the severity of the energy problem can be considerably diminished by raising the energy efficiency of appliances and by managing their peak load demands. By increasing the efficiency standards currently coming into force for appliances, such as clothes washers, water heaters, and air-conditioners, it is estimated that the construction of 170 new 300 MW-power plants can be avoided.

Two issues commonly recognized by industry as barriers to the introduction of more efficient refrigerators and air conditioners are the prohibitive cost of devices that improve their efficiency and the increase in size that would prevent their installation in normal size homes.

ESI sought to develop an intelligent controller to increase the energy efficiency of refrigerators and air conditioners while solving these issues of cost and size. If the use of energy efficient devices reduces the energy consumption of electric motors in the residential sector by 20 percent, the savings would be nearly 1 Quad (10E15 Btu). More than 60 percent of this would come just from energy efficiency improvements in air conditioners and heat pumps using such devices as ESI's intelligent controller. To accomplish this ESI brought the benefits of low cost, high performance electronics to the development of an intelligent controller.

Project Objectives

The objectives as defined in the contract were to:

- Increase the efficiency of compressors used in typical residential refrigerators from 5.4 EER to 7.0 EER by the use of an innovative controller that converts single-phase electrical supply to three-phase power to run the compressor. This would be a 30 percent improvement in efficiency on a power rating of ~200 watts.
- Increase the efficiency of compressors used in typical residential and light commercial heat pumps by 30 percent using a similar controller on a power rating of ~4000 watts.
- While we set no specific economic objectives for the project, ESI identified early in the program that the high cost of efficiency improvement devices is a barrier to market acceptance and we developed our design to meet certain cost considerations. Specifically ESI established a goal of developing the intelligent controller with a selling price of $80 per ton for 100,000 units per year for units above one ton of cooling capacity, to the end user.

Project Outcomes

- For refrigerators, our modeling and analysis results showed that it was only possible to increase efficiency by about ten percent. Our models showed that the annual savings would be on the order of $4 to 5 a year. By comparison, the cost of the controller was too high to make this a practical solution. Based on these results, we made a mid-course correction in the research direction to drop refrigerators from further development and to replace them with development of controllers for residential and light commercial heat pumps.
- For A/Cs, our modeling and analysis results of a 3-ton air conditioner (A/C) showed that it was possible to increase efficiency by 30 percent. Our models showed that the annual savings would be on the order of $90 per year, based on U. S. Department of Energy (DOE) Climate Region 4 and an energy cost of $0.08 per kilowatt hour (kWh).
- For heat pumps, our modeling and analysis results showed that it was also possible to increase efficiency by 30 percent. Our models showed that the annual savings would be on the order of $180/yr. This is twice what we found we could get with A/Cs, because the unit can be used year-round.
- We verified that the compact size of the electronic controller made it possible to install it inside the existing cabinets of both heat pumps and A/Cs.
- We discovered that our controller has a low power factor. This was not unexpected, because this is typical of all rectifier input power circuits. It is possible to increase the power factor by installing a suitable filter, but we did not do that in this contract.
- Laboratory testing on a 2-ton heat pump verified that the electrical performance of the heat pump using the controller matched the expectations in the model. For example, when the controller reduced the speed of the compressor, the power requirements of the compressor dropped proportionately.
- Laboratory testing conducted on a three-ton A/C also verified that the electrical performance of the controller matched the expectations of the model.
- Independent laboratory testing was conducted in accordance with Air Conditioning and Refrigeration Institute ARI 210/240-94 on an unmodified 3-ton 3-phase A/C to establish the baseline efficiency. Our controller was installed and the efficiency tests were repeated. Results showed an improvement in efficiency of 19 percent, assuming a degradation coefficient of 0.25.
- Separate laboratory testing found that switching from single-phase to three-phase compressor motors resulted in an average increase in efficiency of four percent.
- We discovered that for heat pumps or A/Cs between one and five tons, we could sell the controller for an installed price of approximately $100/ton. For heat pumps and A/Cs 5 tons and above, we are able to meet our target of $80/ton.

- At 105°F, the controller did not improve the energy efficiency when operating at full load. However, the controller can operate the A/C at reduced speed with proportionately reduced peak electrical demand. For example, when operating at half speed, the power requirements dropped from 5.5 kW to 2.5 kW.

Conclusions

- Using the controller in heat pumps and A/Cs is very cost-effective, providing a return on investment of less than two and four years, respectively. In California, where the electricity rates are even higher than in our model, the return on investment will be even sooner.
- It is not necessary to increase the physical size of heat pump or A/C enclosures to accommodate the installation of our controller. This is important because other mechanical solutions that provide similar benefits may require significantly larger enclosures and comparably increased costs.
- Using this controller in refrigerator applications is not cost-effective.
- Installing a filter will improve the power factor and make the device more acceptable in widespread application.
- Although the independent laboratory tests compared the efficiency of 3-phase A/Cs, they did not account for the additional four percent improvement that we found could be obtained by switching from single-phase to 3-phase compressors.
- Combined with the 19 percent efficiency improvement (assuming a degradation coefficient of 0.25) observed on the 3-phase A/Cs, we project an overall improvement of 23 percent, which is more than 75 percent of our original target of 30 percent.
- Discussions with A/C and heat pump manufacturers revealed that it is unlikely that they will replace single-phase compressors with 3-phase compressors in the U.S. residential market. Given this inertia, it does not make sense to pursue our 3-phase controller for residential heat pumps or A/Cs at this time.

Benefits to California

In California, the successful commercialization of intelligent controller technology has the potential of providing a 20 percent savings (nearly 5,000 GWh per year) in the energy consumed by residential air conditioners and heat pumps. And because air conditioners are primarily responsible for the large peak demand in diurnal system load profiles, which can result in blackouts and brownouts, use of the controller could increase the reliability and quality of the power system while decreasing the number of future power plants needed in the State. In addition, controller commercialization could provide major benefits to California's economy through the generation of jobs and increased tax revenue while reducing the State's reliance on imported electricity.

Recommendations

- Test the performance of the intelligent controller with filtering designed to improve power quality.
- Test and analyze the controller's effect on the energy consumption of compressors and other equipment.
- Conduct a side-by-side comparison of two heat pumps, with and without the controller, both in the laboratory, and in the field for the period of one year. The purpose of this comparison is to get a better measure of the energy efficiency than is provided by the standard laboratory tests of SEER and will include a measurement of the degradation coefficient.
- Conduct field tests with a statistically useful number of units in small commercial applications in California. The purpose of these tests is to verify the energy efficiency, to determine the reliability and durability of the system and to assess its ability to reduce peak demand.

Abstract

This report, entitled "Increased Energy Efficiency of Air Conditioners and Heat Pumps using Advanced Power Electronics" summarizes research done in the Public Interest Energy Research (PIER) Program for the project Increased Energy Efficiency of Refrigerators and Air Conditioners Using Advanced Power Electronics under Contract #500-98-021.

In this project, Energy Savers International (ESI) generated several power electronics concepts, which were then evaluated, using modeling and analysis tools, at the circuit and system level. ESI selected a multi-phase, multi-speed controller concept as the best concept for improving the energy efficiency of air conditioners and heat pumps and used this concept to develop an intelligent controller using advanced power electronics hardware and software. ESI had an off-the shelf air conditioner tested, before and after installation of the ESI controller, by a reputable independent test laboratory (BR Laboratories) to obtain independent verification of their results. These tests followed Air Conditioning and Refrigerator Institute (ARI) 210/240-94 Standard guidelines to measure Seasonal Energy Efficiency Ratio (SEER). Using the equations and assumptions in that standard, SEER calculated from the test results showed a total improvement of 23 percent, assuming a degradation coefficient of 0.25. Because of linear extrapolations involved in calculating SEER in the ARI Standard, all benefits of three-phase operation were not accounted for. ESI recommends that the next step in validating the energy efficiency increase would be to field test air conditioners and heat pumps to verify the energy efficiency, to determine the reliability and durability of the system, and to assess its ability to reduce peak demand. Data generated through these field tests would be useful in developing a commercial product.

1.0 Introduction

1.1. Need for an Intelligent Controller Technology:

Assuming that the growing energy needs of the nation are met only through building additional power plants, an estimated 1300 new power plants of 300MW each will be needed by the year 2020. However, the severity of the energy problem can be considerably diminished by raising the energy efficiency of appliances and by managing their peak load demands. By increasing the efficiency standards currently coming into force for appliances such as clothes washers, water heaters, and air-conditioners, it is estimated that the construction of 170 new 300MW-power plants can be avoided.[1].

California's serious energy situation requires more near term solutions. The San Jose Mercury reported in its February 25, 2001 issue "*When millions of air conditioners click on this summer, California could be in even worse trouble. The forecast calls for widespread blackouts, unless the state finds a way to supply enough power*." Analysts have forecast a shortfall this summer of 5,000 megawatts while some predict it may be as much as 7,000 megawatts.[2]

Several research studies indicated that residential air conditioners, despite their relatively lower annual utilization rates, are primarily responsible for the large peak in diurnal system load profiles.[3] Modifying or altering the diurnal system load profile as a viable means of load shaving in commercial buildings has attracted the attention of many researchers in the past.[4,5,6]

Reddy, Norford and Kempton identified that the single-family residence is where peak-shaving schemes can be most effectively implemented. [4] Peak sharing schemes can be most effectively implemented in a single-family residence. While there are many ways to reduce peak loading, Reddy et al, indicate that increasing the efficiency of air conditioners leads to both peak load reduction and energy conservation. In addition, it saves residential customers real dollars by decreasing monthly electricity bills.

The energy savings potential of increased of air conditioner and heat pump efficiency in the residential sector is quite large

In California, there is a potential saving of nearly 5,000 GWh per year in electrical energy consumption by air conditioners, heat pumps, and blowers in the residential sector. In commercial sector there is a saving of about 6400 GWh. Information on total energy consumption came from California Energy Commission's reports.

Table 1 shows the electrical energy savings in the residential sector.

Table 1: Electrical Energy Savings in the Residential sector

	Year	
	2000	**2010**
Total electrical energy consumed in the residential sector in California in GWh (Ref. #8) (A)	77,633	92,416
Electrical energy consumed by air conditioners, heat pumps and blowers (C=27% % of A)	20,628	24,555
Potential energy savings in Cal. by ESI and similar controllers in GWh (C= 20% of B)**		4,911

**Electrical energy consumed by air conditioners, heat pumps, and blowers is 27 percent of total electrical consumption in the residential sector. Potential energy savings due to intelligent controllers is calculated to be 20 percent of electrical energy consumed by air conditioners, heat pumps, and blowers.

Table 2 shows the electrical energy savings in the commercial sector.

Table 2: Electrical Energy Savings in the Commercial Sector

	Year	
	2000	**2010**
Total electrical energy consumed in the commerciall sector in California in GWh (Ref. #8) (A)	99,259	118,802*
Electrical energy consumed by air conditioners, heat pumps and blowers (C=27% % of A)	26,799	32,076
Potential energy savings in Cal. by ESI and similar controllers in GWh (C= 20% of B)**		6,415

* California Energy Demand 20002-2012 Forecast

** Potential energy savings due to intelligent controllers is calculated to be 20 percent of electrical energy consumed by air conditioners, heat pumps, and blowers in the commercial sector also.

1.2. Project Objectives

ESI's overall goals were to develop economically viable, energy-efficient technologies in the residential and light commercial sector while launching a successful business in the energy-efficient appliance markets.

The objectives as defined in the contract were to:

- Increase the efficiency of compressors used in typical residential refrigerators from 5.4 EER to 7.0 EER by the use of an innovative controller that converts single-phase electrical supply to three-phase power to run the compressor. This would be a 30 percent improvement in efficiency on a power rating of ~200 watts.
- Increase the efficiency of compressors used in typical residential and light commercial heat pumps by 30 percent using a similar controller on a power rating of ~4000 watts.
- While we set no specific economic objectives for the project, ESI identified early in the program that the high cost of efficiency improvement devices is a barrier to market acceptance and we developed our design to meet certain cost considerations. Specifically ESI established a goal of developing the intelligent controller with a selling price of $80 per ton for 100,000 units per year for units above one ton of cooling capacity, to the end user.

1.3. Report Organization

This report summarizes the research work done in the PIER program to improve the efficiency of air conditioners and heat pumps using advanced power electronics. Section 2.0 – Project Approach provides an overview of concept generation, evaluation, and selection. It then describes the approach taken to realize the concept in hardware and software. Section 3.0 - Project Outcomes identifies and discusses the major results from this research program. Each objective and outcome meeting that objective is given. Section 4 – Conclusions and Recommendations presents final conclusions derived from the research conducted during this project along with recommendations on actions to take the technology to the next stage.

The report contains six appendices:

Appendix I	Modeling Analysis
Appendix II	Independent Testing Laboratory Final Report
Appendix III	ARI Standard 210/240-94: SEER Calculations and Link to ARI Website
Appendix IV	Improvements in Seasonal Energy Efficiency Ratio (SEER) by Intelligent Controller Technology
Appendix V	Residential Building Model Used for Peak Reduction Strategy Development
Appendix VI	Additional Result: Peak Loading Strategy

2.0 Project Approach

2.1. Theoretical Problem

Figure 1shows the distribution of ambient temperature in the cooling season, according to ARI 210/240-94 for region 4. More than 95 percent of the time, ambient temperature is less than 98°F. This means that the air conditioner operates at less than full load most of the time.

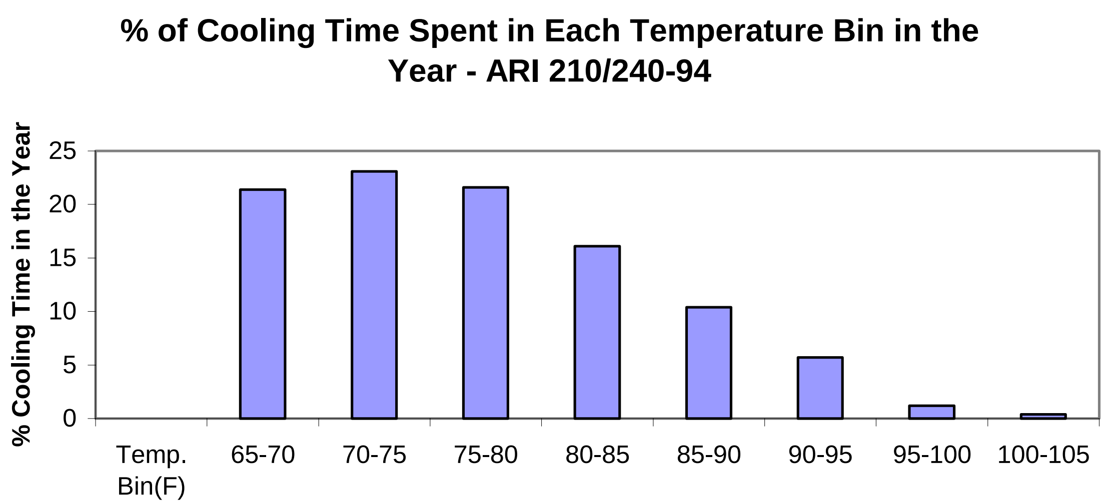

Figure 1: Distribution of Cooling Hours in the Year Used in ARI 210/240-94 Calculations (Region 4)

Figure 2 shows the fraction of full load at which the air conditioner operates resulting in electrical load mismatch.

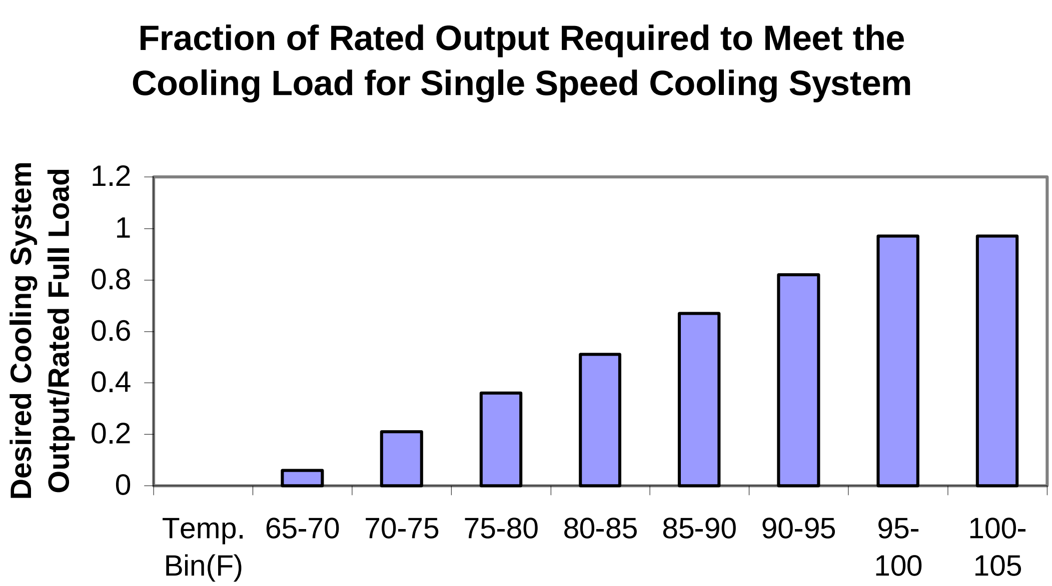

Figure 2: Air conditioner Operates at 1/2 Load or Less for Most of the Year

An important point to note from Figure 1and Figure 2 is that not only does the air conditioner operate most of the year at fractional load, but it operates at less than 50 percent load for significant amounts of time.

The capacity of an air conditioner increases as the ambient temperature decreases because of its inherent thermal properties (Figure 3). But building load decreases with the decreasing ambient temperature. The difference between the capacity of the air conditioner and the cooling load of the building increases as the ambient temperature decreases resulting in huge difference between capacity and cooling load during most of the cooling period in the year. This results in thermal capacity mismatch.

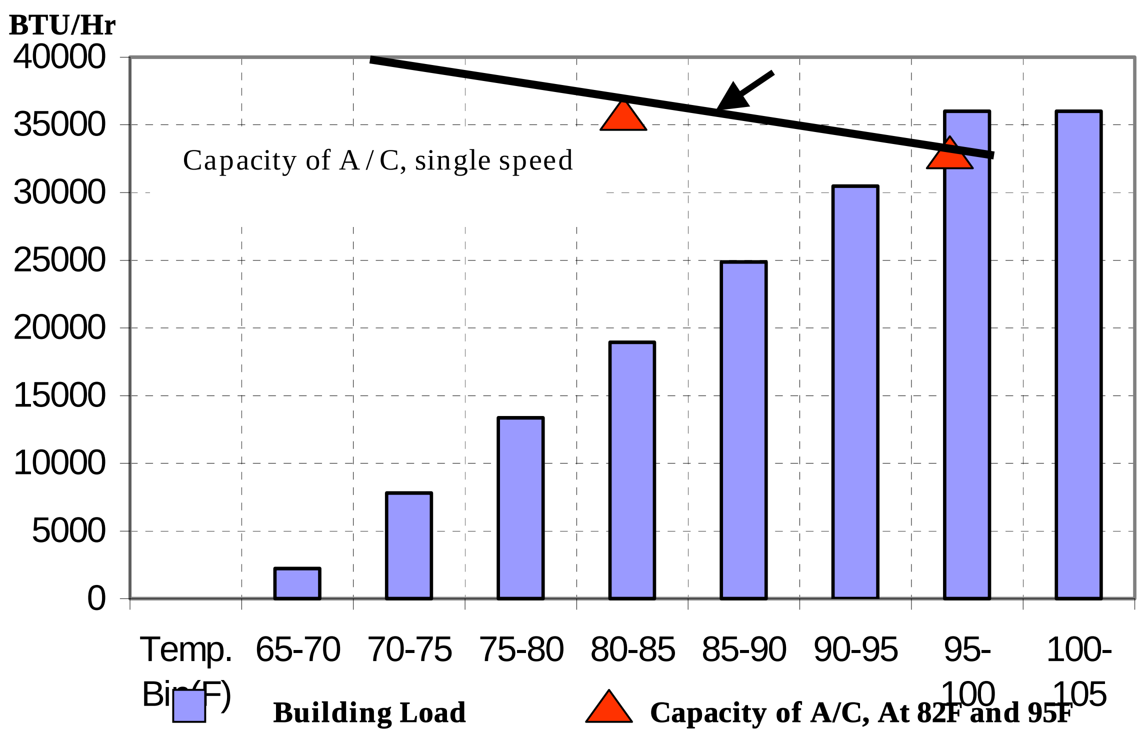

Figure 3: Data Points (Red Triangles) from BRL Test Measurements on 3-Ton Air Conditioner

Note: In current technology, an air conditioner runs at a single speed. Capacity increases and the load decreases as the ambient temperature decreases, causing huge difference between capacity and cooling load at most operating temperatures. Data points (red triangles) are from BRL test measurements on a three-ton air conditioner [10].

These two mismatches--electrical load mismatch and thermal capacity mismatch--result in significantly decreased energy efficiency in typical air conditioners, heat pumps and refrigerators, providing the rationale for this research project.

2.2. ESI's Strategy and Concepts

In current technology, single-phase permanent split capacitor (PSC) motors drive air conditioners and heat pumps in residential applications. These PSC motors have two serious drawbacks.

- Although PSC motors can be designed for high efficiency, it is only at one load condition and one speed. Efficiency drops rapidly as the load on the motor decreases. Since the motor in an air conditioner primarily works at fractional load, this negates any improved efficiency.
- PSC motors are unsuitable for running at different speeds because of the detuning of the capacitor used to optimize its performance.

ESI's strategy was to use three phase motors instead of single-phase PSC motors. Three phase motors have the characteristics needed to increase energy efficiency because, unlike PSC motors, they maintain high efficiency even at fractional loads. And energy efficiency increases if the compressor is run at multiple speeds to match the load. Running the compressor at three speeds provides even higher energy efficiency as well as the added benefit of peak demand reduction.

Program managers at the California Energy Commission and ESI structured a program to achieve the project objective of developing an intelligent controller that would increase energy efficiency by 30 percent. In this program, 13 technical tasks and three reporting tasks were defined with deliverables for each important technical task.

Controller development progressed in four phases:

- Controller design
- Circuit board fabrication
- Component (circuit boards and motors)
- Equipment testing
  - Modifying a 2-ton heat pump and testing it with the controller.
  - Testing of off-the-shelf air conditioners before modifying with the ESI controller
  - Modifying an off-the-shelf air conditioner with the ESI controller and then testing

In Task 2.1 - Concept Generation and Evaluation, we generated several power electronics concepts that were then simulated on circuit simulation tools, such as SABRE and ISPICE, at ESI.

We chose two concepts for further evaluation:

- Three-phase induction motor driving a compressor and operating at single speed
- Three-phase induction motor driving a compressor and operating at multiple speeds

Power electronics for these two options differed greatly in circuit topology.

Ed Vineyard, ESI's consultant in this project for system studies, modeled, and analyzed the concepts. He used the validated models available for public use from the Oakridge National Laboratory to simulate and evaluate the performance of the candidate concepts.

To determine the cooling and heating efficiencies of the air conditioner / heat pump using concepts mentioned above, it was first necessary to calculate the energy efficiency ratio (EER) at the rating temperatures as specified in the Air-Conditioning and Refrigeration Institute (ARI) Standard 210 / 240-94. Once the EER had been determined, we used the National Institute of Science and Technology (NIST) Seasonal Energy Efficiency Ratio (SEER) and Heating Seasonal Performance Factor (HSPF) models to determine the SEER for air conditioners and HSPF for heat pumps. The SEER model requires the capacity and energy consumption at 82°F and 95°F. To make temperature consistent, SEER is calculated using bin weather data. Region 4, which is used as the national average for calculating HSPFs, was selected for this study. Appendix I gives details of Vineyard’s modeling and analysis studies.

The results of his system analysis decided the choice of hardware and software developed in this program. He concluded that a controller driving a three-phase air conditioner or heat pump at varying speeds could increase energy efficiency by 30 to 40 percent.

Vineyard also conducted similar studies refrigerators and concluded that the value of energy saved by an ESI controller in a refrigerator is only $4 per year. Since our estimate that in quantities of 100,000 per year, the manufacturing cost per controller would be about $20, we concluded that it was not a practical, cost effective solution to increase the energy efficiency of refrigerators with our controllers.

Vineyard's analysis also showed that heat pumps possibly present the best near term markets for ESI's controllers because heat pumps operate all year round and can save more than $180 per year.

To use our limited resources profitably, we requested the California Energy Commission to change the work statement to replace refrigerators with air conditioners at the first Critical Project Review. The request was granted and the work statement revised.

With the choice of the operating mode determined from system studies, work in this project progressed to the design and fabrication of an intelligent controller.

ESI designed the controller with two major functional blocks:

- A power stage handling power switching functions
- A controller stage that had all the intelligence functions, including the gating signals required in the power stage.

To accomplish all the processing functions, we selected a new signal-processing chip from a major chip manufacturer that had large processing capabilities and potential for low cost. Unfortunately there were persistent electrical noise problems that could not be resolved. In addition, the power stage was blowing up. This extended the schedule and drained the budget.

Taking a fresh approach that included changes in personnel and hardware design, the major functions were separated into two boards:

- The power stage to handle switching of the power transistors
- An intelligent controller board to perform control functions.

TB Woods, a manufacturer and a supplier of power boards to OEM customers, provided prototype power boards that met our requirements. Integrated power board technology is making rapid progress in cost reduction, a number of large manufacturers produce highly integrated power stages. Using the design approach of separating the power and control functions allowed ESI to make use of this rapid progress in power boards without having to make significant changes in the controller itself. The TB Woods power board controls speed, senses outside temperature, and performs the algorithms needed to control the air conditioner. ESI designed, fabricated, and tested the controller board in-house.

Figure 4 shows schematics of the current technology and of the new technology developed during this program. In current technology, a Permanent Split Capacitor (PSC) motor is driven by a single-phase supply at a single frequency (line frequency of 60 Hz). In ESI's technology, the controller runs a three-phase motor at multiple speeds, drawing power from single phase 60 Hz line supply available in residences or a three-phase supply, if available. We designed the controller with the necessary interfaces to provide inputs to the controller.

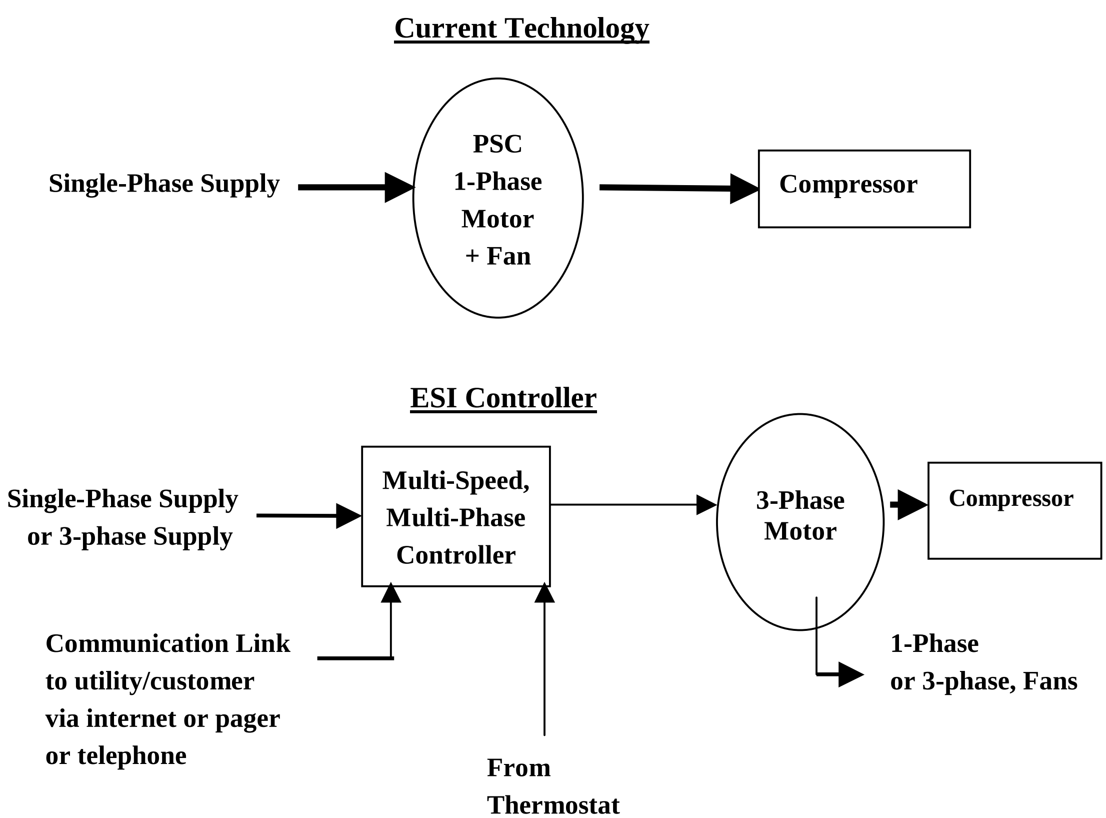

Figure 4: Comparison of Air-Conditioning/Heat Pump Controller Strategies: Current technology vs intelligent controller technology

ESI studied both new and retrofit residential and commercial applications.

Laboratory tests were conducted by ESI with the control and power boards were also installed in a two-ton off-the-shelf heat pump and on a three-ton A/C.

The control and power boards were installed on a three-ton off-the-shelf air conditioner, which underwent independent laboratory testing at BR Labs both before and after controller installation to determine the magnitude of the energy efficiency improvement. At this time, the Commission Contract Manager requested that we test the air conditioner at 105°F outdoor temperature in order to determine how well the controller would address the high temperature conditions and peak load issues found during California summers.

3.0 PROJECT OUTCOMES

ESI verified that the compact size of the electronic controller made it possible to install it inside the existing cabinets of both heat pumps and A/Cs.

ESI purchased an off-the–shelf three-ton air conditioner and a two-ton heat pump from a local distributor, which were then modified by installing intelligent controllers. Preliminary in house testing was conducted on the units' logic circuits and interfaces. These tests proved that ESI's controllers could be easily integrated with existing electrical controls in off-the-shelf equipment.

Table 3 provides the specifications fro the two-ton heat pump.

Table 3: 2-Ton Heat Pump Specifications

Make		Friedrich
Model Number		YL24J35A-1
Power		200/230 volts, 60 Hz, 1-Phase
Cooling	**BTU/hr**	23,800/24,000
	EER	9.0/9.0
	Amps	12.0/13.0
Heating	**BTU/hr**	22,000/23,000
	Amps	10.4/11.5

Figure 5 shows the heat pump fitted with the ESI controller (see circled area denoted by arrow).

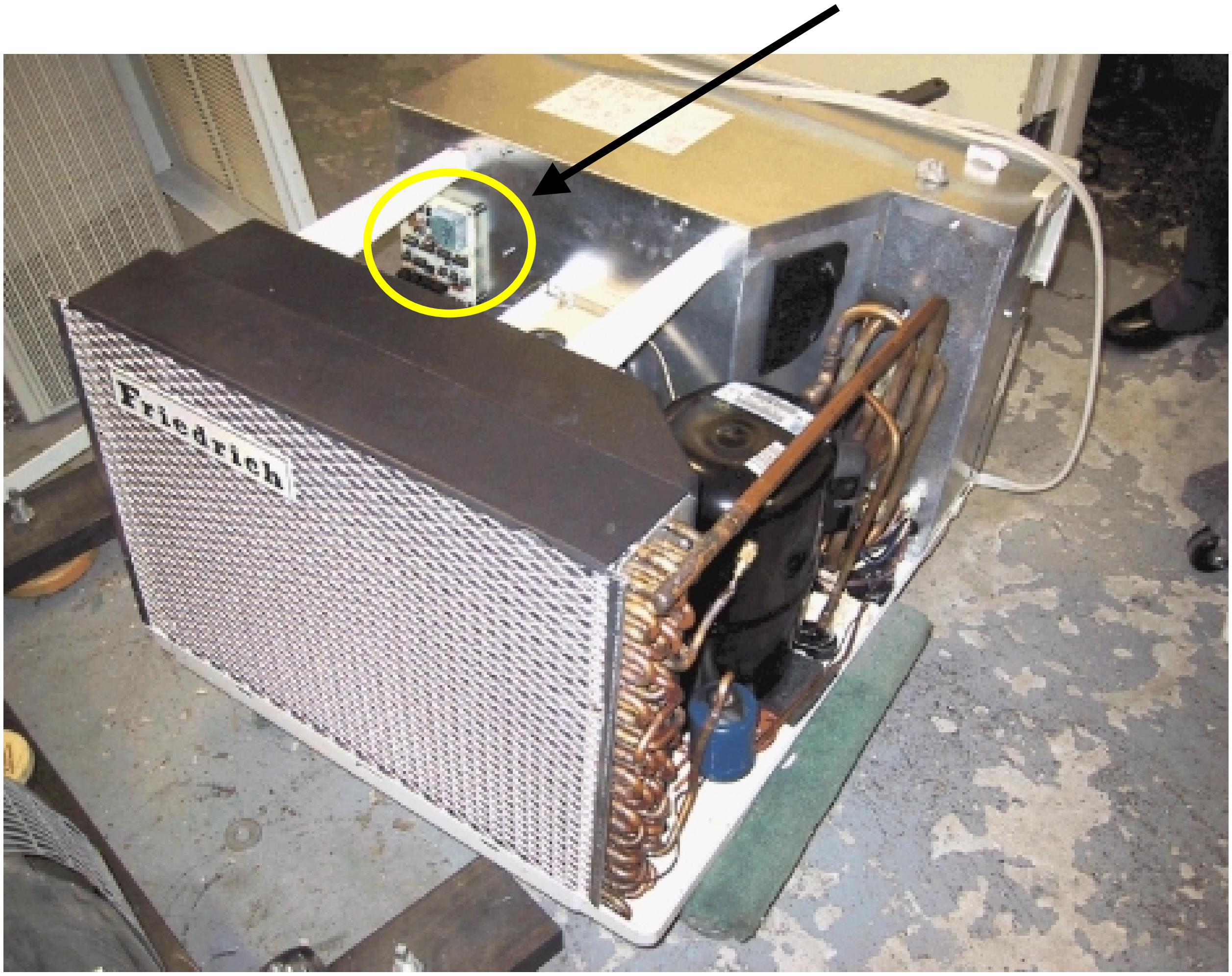

Figure 5: Two Ton Heat Pump Fitted with the ESI Controller

The Dayton Electric Manufacturing Company (Niles, Illinois 60714) manufactured the air conditioner. Table 4 provides the specifications for the unit.

Table 4: 3-Ton Air Conditioner Specifications

Stock Number	3Ujo2 (outdoor use)
Model Number	mlka-a036ck 006
Serial Number	5661F260018613
Manufacturing Date	06/00
Power Supply	208/230 volts, 3-phase, 60Hz
Operating Volt Range	187-253 volts
Compressor	208/230 volts, 3-phase, 13 amps
Outdoor Fan	208/230 volts, 1-phase, 2 amps, 1/3 hp (0.249 KW)
Indoor blower	208/230 volts, 1-phase, 4 amps, ½ hp (0.373 KW)

Figure 6 shows the ESI controller (see circled area denoted by arrow) installed in a three-ton air conditioner. There was no increase in footprint because the controller easily fit inside the electrical cabinet.

Figure 6: Three-Ton Air Conditioner Fitted with the ESI Controller

Laboratory testing on a two-ton heat pump verified that the electrical performance of the heat pump using the controller matched the expectations in the model. For example, when the controller reduced the speed of the compressor, the power requirements of the compressor dropped proportionately.

- Laboratory testing conducted on a three-ton A/C also verified that the electrical performance of the controller matched the expectations of the model.
- We discovered that our controller has a low power factor. This was not unexpected, because this is typical of all rectifier input power circuits.
- Independent laboratory testing was conducted in accordance with ARI 210/240-94 on an unmodified 3-ton 3-phase A/C to establish the baseline efficiency. Our controller was installed and the efficiency tests were repeated. Results showed an improvement in efficiency of 19 percent. This number is less than what the modeling predicted.

ESI chose BR Laboratories Inc. (BR Labs or BRL), Huntington Beach, California to conduct efficiency tests under the guidance of the California Energy Commission Project Manager. BR Lab is a test laboratory performing testing and evaluation of home appliances for government agencies and the air conditioning industry. They conducted tests before and after installation of the ESI controller on an off-the-shelf three-ton air conditioner bought from a local vendor. Appendix II contains the test laboratory report with the testing method used and resulting data.

These tests followed ARI Standard 210/240-94 (Appendix III), which is widely accepted and commonly used by air conditioning industry for calculation of the Seasonal Energy Efficiency Ratio (SEER). SEER is the ratio of total cooling provided [Btu] in one year to the total electrical energy supplied [kWh]. Improvement in SEER indicates energy saved.

Table 5 shows the results of these tests. Rows containing 60 Hz data show the performance of the unit without the controller. The table shows how the performance of the unit varies with changes in frequency. At 82° / 65° outdoor conditions, EER increases from 9.8 to 10.6 as the frequency drops from 60 to 35 Hz. Capacity and power requirements (watts) drop proportional to the frequency. Since the capacity of the unit is based on design temperatures of 95°F, using our controller will enable the air conditioner to match the load with a significant savings in energy and power when the outdoor temperatures are moderate.

Table 5: Test Results at 82°/65° and 95°/75°

Outdoor Condition, 82°/65°						
Db Temp. (°F)	Frequency (Hz)	Capacity (Btu/h)	Power (Watts)	EER (Btu/Wh)	Btus (%)	W (%)
82	60	35142	3600	9.8		
82	50	28027	2940	9.5	80	82
82	40	23336	2240	10.4	66	62
82	35	21173	2000	10.6	60	56
Outdoor Condition, 95°/75°						
Db Temp. (°F)	Frequency (Hz)	Capacity (Btu/h)	Power (Watts)	EER (Btu/Wh)	Btus (%)	W (%)
95	60	33133	4190	7.9		
95	50	25911	3380	7.7	78	81
95	40	20477	2610	7.9	62	62
95	35	16970	2280	7.4	51	54

At 95°F / 75°F outdoor conditions, there appears to be no benefit from using the controller. Even though EER is the same at 60 and 40 Hz, the capacity is reduced and the unit is unable to meet the load.

Figure 7 uses test lab data to graphically show the relationship between ambient temperature and EER. The EER is plotted at 9.8 and 10.6 for 82°/65° outdoor conditions and 7.9 and 7.4 for 95°/75° outdoor conditions. Using the ARI method, ESI plotted the high-speed and low-speed EER lines.

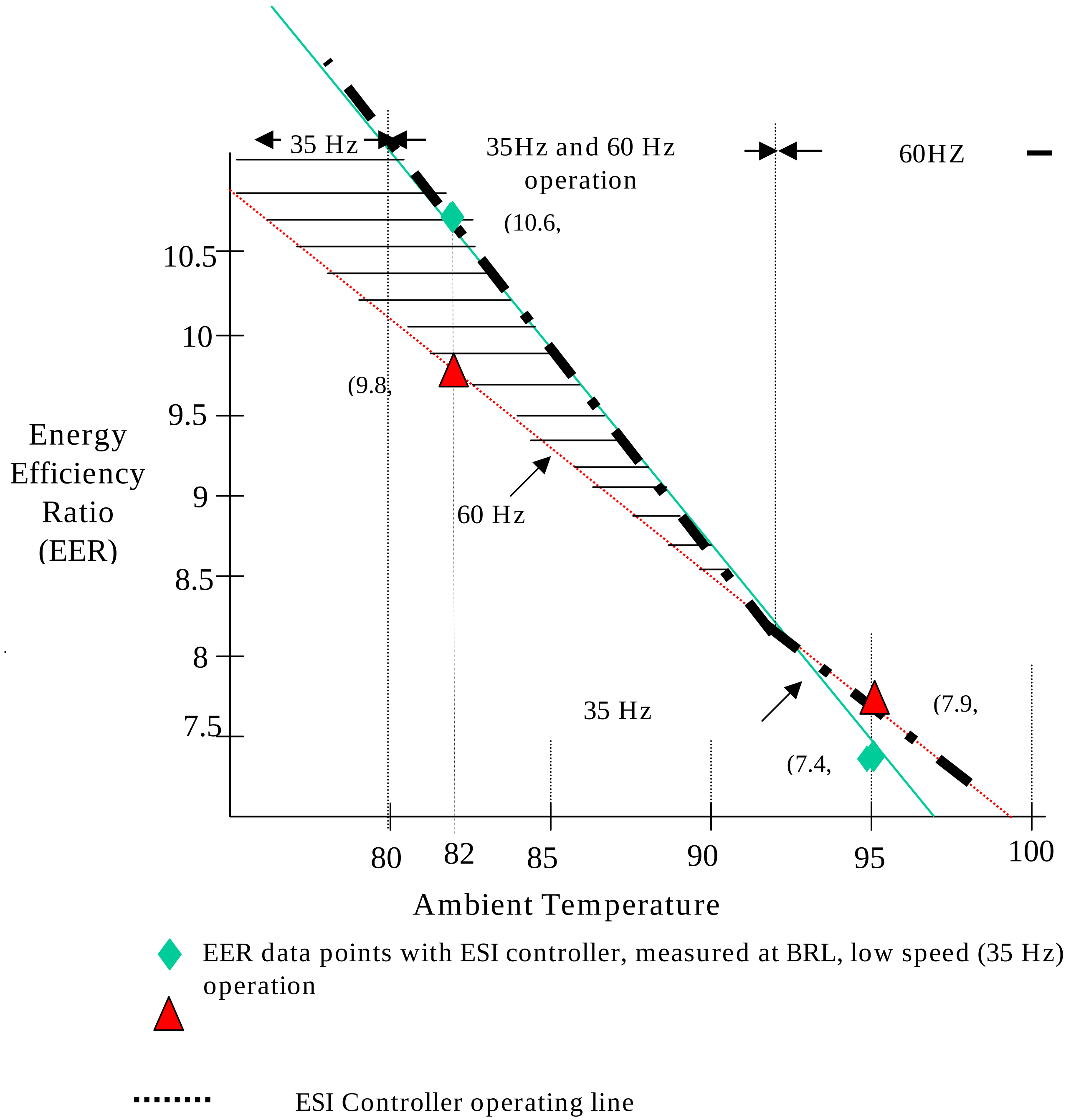

Figure 7: Relationship between Ambient Temperature and EER

The figure illustrates how the controller operates under outdoor conditions. The bold line shows how the controller matches itself to the load by changing frequency. At conditions below 82°/65°, the controller will be at 35 Hz, but at conditions between 82°/65° and 95°/75°, the controller selects the speed that best matches the load. At conditions above 95°/75°, the controller will be bypassed and the unit will operate at 60 Hz. The energy savings obtained occur between the bold line and the line for high-speed operation. The savings are due to two factors: an improvement in the EER and the continuous operation of the air conditioner as the controller allows it to better match the load, thus minimizing on/off cycling and its attendant losses.

The ARI method (see Appendix IV for more details) calculates SEER based on, EER and cycling losses, and includes a factor to account for on-off cycling losses called the degradation coefficient, $\mathbf{C_D}$. Table 6 shows the results of these calculations for degradation coefficients due to cycling losses of 0.25 and 0.07. The ARI method permits using a degradation coefficient of 0.25 when cycling losses for the specific unit are not measured, which was not done. The manufacturer quotes 0.07 for the degradation coefficient.

Table 6: SEER of 3-Ton Air Conditioner Driven by ESI Controller

	SEER – Two Speed 35 Hz and 60 Hz	SEER – Single Speed 60 Hz	Improvement due to Speed Conversion
C_D = 0.25	10.2	8.5	19%
C_D = 0.07	10.5	9.4	12%

At 105°F outdoor conditions, the controller did not improve in energy efficiency when operating at full load. However, the controller can operate the A/C at reduced speed with proportionately reduced peak electrical demand. For example, when operating at half speed, the power requirements dropped from 4.5 kW to 2.5 kW.

Table 7 shows the results of the tests we conducted at 105°/75°. Compared to operation at 95°/75°, capacity and EER are greatly reduced. Power consumption without the controller (60 Hz operation) is the highest, as in Table 6. With the intelligent, controller, power is reduced proportional to capacity. However, in all cases, the unit is unable to meet the cooling load in the building.

Table 7: Test Results at 105°/75°

Outdoor Condition, 105°/75°						
Db Temp. (°F)	Frequency (Hz)	Capacity (Btu/h)	Power (Watts)	EER (Btu/Wh)	Btus (%)	W (%)
105	60	30987	4580	6.8		
105	50	23786	3770	6.3	77	82
105	40	17549	2880	6.1	57	63
105	35	16794	2540	6.6	54	55

4.0 Conclusions and Recommendations

4.1. Conclusions

- It is not necessary to increase the physical size of heat pump or A/C enclosures to accommodate the installation of our controller. This is important because other mechanical solutions that provide similar benefits may require significantly larger enclosures and comparably increased costs.

- Using the controller in heat pumps and A/Cs is very cost-effective, providing a return on investment of less than 2 and 4 years, respectively. In California, where the electricity rates are even higher than in our model, the return on investment will be even quicker.

ESI designed and built an intelligent controller to drive three-phase motors at different speeds and to operate from a single-phase or three-phase energy supply. The controller used innovative and proprietary electronic circuits with the latest processor and power chips for signal and power processing. Successfully tested at ESI's laboratory, the controller demonstrated its efficiency and its capability to drive three-phase compressor motors from either a single-phase or three-phase power supply. Design of the controller was strongly influenced by economic considerations that would allow ESI to achieve its goal of $80/ton of air conditioning in quantities of 100,000/year.

ESI studied the production processes and estimated the cost of manufacturing in large quantities. ESI plans to use the same manufacturing processes as those already in use in manufacturing boards for the computer and communication industry. Because similar boards are manufactured in very large volume in many parts of the world, resulting in very low cost, ESI controller will also be low cost, benefiting from the already established manufacturing lines. A study of cost of materials and manufacturing showed that controllers for A/Cs from 1-5 tons, the end user cost can be about $100 per ton. For sizes from 5 to 30 tons, the end user cost of the controller can be about $80 per ton.

Based on these costs, a three-ton A/C or heat pump would need a controller that would cost $300. Table 8 shows the savings and payback using the controller with an A/C. These savings are based on the SEERs calculated from the EER data taken during our laboratory tests.

Table 8: Improvement in SEER Due to Speed Conversion and Phase Conversion.

	C_D = 0.25	C_D =0.07
SEER Two Speed	10.2	10.5
SEER Single Speed	8.5	9.4
Improvement Due to Speed Conversion	19%	12%
Improvement due to Phase Conversion	4%	4%
Total Efficiency Improvement	23%	16%

Since we did not measure the performance of a heat pump, we can only estimate the savings. Using the assumption that a heat pump runs about twice as many hours as an A/C, the savings would be twice as much and the payback half as long. The savings and payback for units greater than five tons would be about 20 percent larger due to the lower costs per ton for the controller (Table 9).

Table 9: Intelligent Controller Payback Calculations

QUANTITY [UNITS]	AIR CONDITIONERS				HEAT PUMPS			
	NATIONAL AVG. DESIGN HOURS [h/yr]:		CALIFORNIA AVG. DESIGN HOURS [h/yr]:		NATIONAL AVG. DESIGN HOURS [h/yr]:		CALIFORNIA AVG. DESIGN HOURS [h/yr]:	
	1000		1800		2000		3600	
	standard unit	unit w/ ESI controller	standard unit	unit w/ ESI controller	standard unit	unit w/ ESI controller	standard unit	unit w/ ESI controller
Design Capacity,C [Btu/h]	36000	36000	36000	36000	36000	36000	36000	36000
SEER [Btu/(Wh)]	8.5	10.2	8.5	10.2	8.5	10.2	8.5	10.2
C/SEER [W]	4235	3529	4235	3529	4235	3529	4235	3529
(C/SEER)* Des.Hrs [Wh/yr]	4.24E+06	3.53E+06	7.62E+06	6.35E+06	8.47E+06	7.06E+06	1.52E+07	1.27E+07
Electric Cost [$/(kWh)]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ann. Operation Cost [$/yr]	423.5	352.9	762.4	635.3	847.1	705.9	1524.7	1270.6
Delta [$/yr]	-	70.6	-	127.1	-	141.2	-	254.1
Payback [yr]	**-**	**3.4**	**-**	**1.9**	**-**	**1.7**	**-**	**0.9**

Cooling cost = Design Cap./SEER) * Design hours * Electric Cost * 1/1000

where Design Capacity = 36000 Btu/hr; Electric Cost = 0.10 $/kWh and Controller Cost = $240

Payback period = Controller Cost / Difference in Operation Cost (Delta)

NOTE: For heat pumps, the payback calculation is the same as for cooling only, but the period is half of that for A/C, because the controller saves energy in both heating and cooling modes

Installing a filter will improve the power factor and make the device more acceptable in widespread application. It is possible to increase the power factor by installing a suitable filter, but we did not do that in this contract. The addition of a passive filter is quite straight forward, but it will increase the cost by about ten percent and the weight by about 20 percent. An active controller will add only very small amount to weight, but is more expensive. The power quality issue becomes important for the utility as the penetration of motor controllers, not only in HVAC applications but in all power electronic motor controller applications, becomes significant. ESI will design and implement these filters as the utilities in domestic and international markets demand.

Although the independent laboratory tests compared the efficiency of 3-phase A/Cs, they did not account for the additional four percent improvement that we found could be obtained by switching from single-phase to three-phase compressors (Appendix IV). Combined with the 19 percent efficiency improvement observed on the three-phase A/Cs, we project an overall improvement of 23 percent, which is more than 75 percent of our original target of 30 percent.

4.2. Benefits to California

Successful commercialization of this technology will benefit California by significantly reducing electrical consumption and enhancing the value of electricity to end-users. It will also help decrease the peak demand, providing short term benefits by preventing rolling blackouts and decreasing the number of future power plants needed in the State.

4.2.1. Energy Savings

In California, the potential exists to save nearly 5,000 GWh per year in electrical energy consumption by air conditioners and heat pumps in the residential sector through the use of intelligent controller technology. Total electrical energy consumed in the residential sector (Table 10) came from the California Energy Commission's report "California Energy Demand 2000", supplied by the Commission Project Manager. ESI's intelligent controller technology has the potential to save 20 percent of the total electric energy consumed by air conditioners and heat pumps in California.

Table 10: Potential Annual Energy Savings (Assuming 20% Savings due to ESI Controller)

	Year	
	2000	2010
Total electrical energy consumed in the residential sector in California in GWh **(A)**	77,633	92,416
Potential savings by ESI and similar controllers in GWh **(D= 20% of C)**		4,911

4.2.2. Environmental Benefits:

Table 11 shows the projected annual air emissions reductions resulting from 20 percent reduction in energy consumption of air conditioners and heat pumps resulting from the application of technologies such as the ESI intelligent controller in the Year 2010 (calculated for 5000 gWh per year).

Table 11: Projected Annual Air Emissions Reductions

	United States Thousands of Pounds/Year			California Thousands of Pounds/Year		
Duration	CO_2	NOx	SO_2	CO_2	NOx	SO_2
Per year	104,000	374	677	12,500	44.2	81.2

4.2.3. Improving the Reliability and Quality of Generation

ESI's controller has a feature important to power system reliability. As described earlier, the controller can run peak reduction programs with an existing, low cost thermostat. It is well known that despite their relatively lower appliance annual utilization rates, air conditioners are primarily responsible for the large peak in diurnal system load profiles, which results in blackouts and brownouts. ESI controller offers a technical solution. To implement it in the field, teaming with the utilities and energy service providers is needed. It also requires a tariff structure that encourages peak power demand reduction by the customer.

4.2.4. Impact on State and Local Economies

State and local economies will benefit from the successful commercialization of the controllers. Based on U.S. market projections and the potential international market, sales of controllers could bring revenue of more than $100 million in the fifth year of business. This would represent less than five percent of the world market for an item that would be proprietary to ESI.

Table 12 shows the five-year sales forecasts for air conditioners and heat pumps in the United States (thousands of units) residential market.

Table 12: Five-Year Sales Forecasts for Residential Markets

	2001	2002	2003	2004	2005
Air-Conditioners, Unitary	6,252	6,485	6,755	7,018	7,874
Heat Pumps	1,550	1,609	1,668	1,739	1,908

(From Appliance Magazine's annual forecast – January 2000)

Sales at these projected levels could have the following impacts on the California economy:

<u>Jobs</u> – Approximately 25 percent of the cost of ESI's products will be made in California, which represents approximately $100 million in products manufactured. Therefore, an average $25 million will be spent on labor in California every year to meet ESI's production. If the average job costs $50,000 (including benefits), 500 direct jobs would be created as a result of the proposed work. Using a four to one multiplier to compute the number of indirect jobs (standard for manufacturing jobs), results in the creation of 2,000 indirect jobs for the California economy, a total of 2,500 new jobs created.

<u>Income Taxes</u> – If $25 million of ESI's revenues are paid to employees who are paying the 10 percent income tax in California, $2.5 million a year will be generated in State income tax just for direct jobs. There are four times as many indirect jobs as direct jobs. There are therefore additional tax revenues that will accrue to the State due to these indirect jobs.

<u>Sales Tax Revenue</u> – If ESI sells $100 million a year of goods and they are taxed at eight percent, $8 million will be generated each year in sales tax revenues.

<u>Percentage of Sales</u>: One and a half percent of sales of controllers developed in this PIER project goes to the state treasury, according to the contract between ESI and the State, until three times the contract money (three times $411, 464) has been paid back.

<u>Reduction in Energy Imports</u> – As ESI's products penetrate the California market, the demand for electricity for air conditioners and heat pumps will be reduced. This will in turn reduce the demand for electricity imported into the state and also the need for fossil fuel for generation plants in the state.

4.3. Recommendations

- Test the performance of the intelligent controller with filtering designed to improve power quality.
- Test and analyze the controller's effect on the energy consumption of compressors and other equipment.
- Conduct a side-by-side comparison of two heat pumps, with and without the controller, both in the laboratory, and in the field for the period of one year. The purpose of this comparison is to get a better measure of the energy efficiency than is provided by the standard laboratory tests of SEER and will include a measurement of the degradation coefficient.
- Conduct field tests with a statistically useful number of units in small commercial applications in California. The purpose of these tests is to verify the energy efficiency, to determine the reliability and durability of the system and to assess its ability to reduce peak demand.

5.0 Commercialization Potential

ESI's controller can be integrated in air conditioners and heat pumps – one controller in each appliance. Since ESI's total market size (in number of units) is the same as that of the two appliances, controller market size can be estimated from the size of the market for air conditioners and heat pumps. The following data points apply to the market for controllers:

- About six million new air conditioners and heat pumps were sold in U.S. in 2000 (Appliance Magazine, Jan.2001) and at least about five times that in the international market.
- The value of shipments of HVAC equipment reported in 1996 Annual Survey of Manufacturers is slightly more than $28 billion; air conditioners accounting for $4.6 billion (SIC 35852).
- Appliance Magazine, a trade journal serving this industry forecasts that by the year 2005 the shipment of air-conditioners could reach 7,874,000 units and heat pumps 1,908,000 units. (Table 12).
- As every new air conditioner and heat pump can be fitted with the ESI controller, the total market for controllers is the same as for new air conditioning units (Table 12).

5.1. Pre-commercialization Efforts:

ESI prepared a business plan with the help of Silicon Valley Small Business Development Center in San Jose. It also developed a marketing plan. ESI is actively pursuing implementation of these plans with the goal of building a business based on intelligent controller technology.

The next logical step in bringing this technology to market is to launch a field test program to generate data for final product development and its marketing. ESI will fabricate 100 circuit boards for the controller using the services of contract manufacturers in the valley.

Although market potential is large, barriers to market penetration are also large. In the specific case of ESI, its success depends on obtaining the capital needed to enter the business and produce in the volume required to meet the low-price targets.

6.0 Glossary

A/C	Air Conditioning, Air Conditioner
ACEEE	American Council for an Energy-Efficient Economy
ARI	Air Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BR Labs	BR Laboratories
Btu	British thermal unit
C_D	Degradation Coefficient (**C_D**) is a measure of the efficiency loss due to the cycling of the unit (air-conditioner).
Commission	California Energy Commission
DOE	U.S. Department of Energy
EER	Energy Efficiency Ratio (EER) is the ratio calculated by dividing the cooling capacity of the air conditioner in Btu / hr by the power input in watts at any given set of rating conditions, expressed in units of Btu / Wh
ESI	Energy Savers International
GWh	Gigawatt hour
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz
kWh	Kilowatt hour
NIST	National Institute of Science and Technology
OEM	Original Equipment Manufacturer
ORNL	Oakridge National Laboratory
PG&E	Pacific Gas & Electric
PSC	Permanent Split Capacitor
Quad	One quadrillion (10^{15}) British thermal units (Btus). An amount of energy equal to 170 million barrels of oil. Total U.S. consumption of all forms of energy is about 83 quads in an average year. (1990 Figures)
SEER	Seasonal Energy Efficiency Ratio (SEER) is the total cooling output of a central air conditioner in Btu during its normal usage period for cooling divided by the total electrical energy input in watt-hours during the same period (It includes the effect of degradation coefficient, expressed in units of Btu / Wh.
SOW	Statement of Work
TOU	Time-of-Use (a.k.a. “Time-Dependent Valuation”)

7.0 References

1. New York Times, May 5, 2001

2. San Jose Mercury News, “Worse power problems on the horizon”, Page 1A, February 25, 2001.

3. T.A. Reddy and D.E. Claridge, “Effect of Air Conditioner Oversizing and Control on Electric Peak Loads in a Residence”, Energy, Vol.16, p.1139-1152, 1993.

4. T.A. Reddy, L.K. Norford and W. Kempton, “Shaving Residential Air-Conditioner Electricity Peaks by Intelligent Use of the Building Thermal Mass”, Energy, Vol.16, p. 1001-1010, 1991.

5. I. Andersen and M.J. Brandemuehl, “Heat Storage in Building Thermal Mass: A Parametric Study” ASHRAE Transactions, AN-92-8-3, p. 910-918, 1992

6. K.R. Keenly, J.E. Braun, “Application of Building Pre-cooling to Reduce Peak Cooling Requirements,” ASHRAE Transactions, PH-97-4-1, p. 463-468, 1997

7. American Council For an Energy-Efficient Economy, “Appliance Energy Efficiency”, Technical Report A972, p. 1-1, 1997

8. California Energy Commission Report, “California Energy Demand 2000,” information supplied by Commission Project Manager, June 16, 2001

9. N. Mohan et al, John Wiley, “Power Electronics: Converters, Applications and Design,” p. 92 and 420, 1995

10. R.W. Griffith, "A Study of the Effects and Economics of Capacity Modulation on Seasonal Energy Efficiency Ratios (SEER) for Air Conditioners", ASHRAE, LA-80-1, p. 465-476, 1980

Appendix I

Modeling Analysis

Appendix II

BR Labs Report

Appendix III

ARI Standard 210/240-94: SEER Calculations and Link to ARI Website

Appendix IV

Improvements in Seasonal Energy Efficiency Ratio (SEER) by Intelligent Controller Technology

Appendix V

Residential Building Model Used to for Peak Reduction Strategy Development

Appendix VI

Peak Loading Strategy